Chapter 1
Introduction

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1.1 Introduction

The widespread usage of affordable electricity converted from ocean waves would be a fabulous achievement. Besides that the wave energy converting (WEC) technology would be particularly interesting, it also would have several significant benefits to society, such as:

- It is another sustainable and endless energy source, which could significantly contribute to the renewable energy mix. In general, increasing the amount and diversity of the renewable energy mix is very beneficial as it increases the availability and reduces the need for fossil fuels.
- Electricity from wave energy will make countries more self-sufficient in energy and thereby less dependent on energy import from other countries (note: oil is often imported from politically unstable countries).
- It will contribute to the creation of a new sector containing, innovation and employment.
- Electricity from ocean wave can be produced offshore, which thereby does not require land nor has a significant visual impact.

As the world energy needs will keep on increasing while the fossil fuel reserves are depleting, wave energy will become of significant importance. The demand for it will start when its price of electricity will be right and will then only increase with time.

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1.2 The Successful Product Innovation

In general, there are three key elements to a successful product innovation. It has to be technically feasible, economically viable and desirable/useable by an end-user. In other words, it requires a new functional technology that has a positive business case and that is of use for society. These key elements do not necessarily require being developed at the same time since a developer needs to start somewhere. However, they need to be present in some kind of harmony before an innovation can successfully be launched on the market (Fig. 1.1).

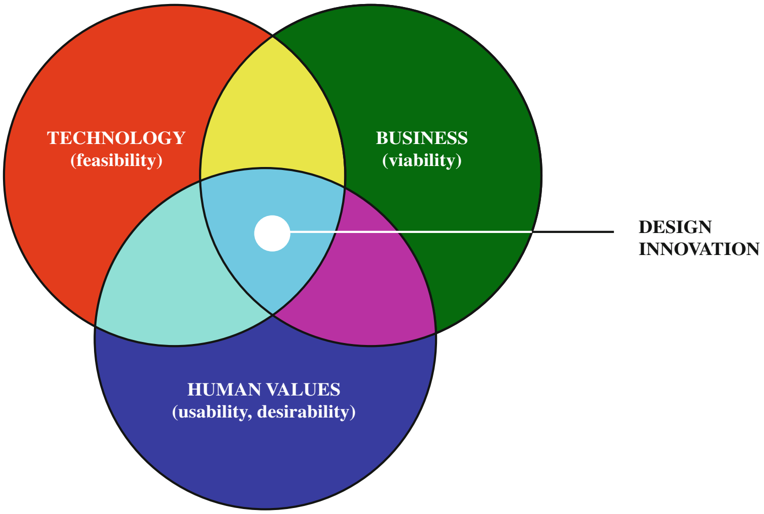

Fig. 1.1 The three key elements of successful product design innovation. Inspired by [25–27]

There is a great demand for renewable energy and a need to diversify the renewable energy mix. This can easily be seen on the significant annual increase in global investment in renewable energy, such as wind and solar. Wave energy has even been additionally stimulated in some countries as they recognise its benefits and great potential. The technology push came mainly in the form of public grants and capital investment in technology development, while the market pull through public market incentives, such as revenue support (the feed-in tariffs) [1, 2]. This indicates that the usability and desirability (or human value) are currently very positive.

An impressive amount of wave energy technologies have been developed over the last 25 years. To give an indication hereof, the list of current wave energy developers at EMEC counts 256 developers [3]. The working principles of most of these technologies can be grouped into a handful of main categories. This just indicates how great the effort has been from the developers (see more in Chap. 2).

The last missing factor for production innovation success is the business potential or economic viability of the wave energy technologies within the frames of the market (with or without incentives). The business case is made based on cost (CapEx and OpEx) and power production calculations (read more in Chaps. 4 and 5). To be able to demonstrate a positive business case, a significant amount of proof (for the calculation) and thereby experience with the WEC is expected to be gathered before. Although some investors can be convinced on the way in the great business potential of a WEC, it will probably still require a decent track record of an offshore full-scale WEC before it will convince a larger market. This is particularly difficult to realise with WECs since the development cost is particularly high (e.g. compared to wind energy) and the development process long. This is especially due to the harsh offshore environment, which requires special equipment and vessels and which is not easily accessible. So, the development process requires a careful balance between technology optimisation and physical progress. The best advice is, therefore, to keep on investigating the economic potential along the development progress as there is no reason to progress if it is absent.

1.3 Sketching WECs and Their Environment

WECs are machines that are able to exploit the power from ocean waves and to convert it into a useable form of energy, such as electricity.

Ocean waves are theoretically relatively well understood and extensively described in literature. However, in practice, it is very difficult to accurately describe, reproduce and predict the exact environmental conditions at a certain offshore location. This is due to its complexity and the large amount of environmental parameters that can have a significant influence on it (read more about this in Chap. 3).

In Fig. 1.2, the different metocean parameters affecting the marine environment are sketchily presented, together with the primary sub-systems of a (floating) WEC.

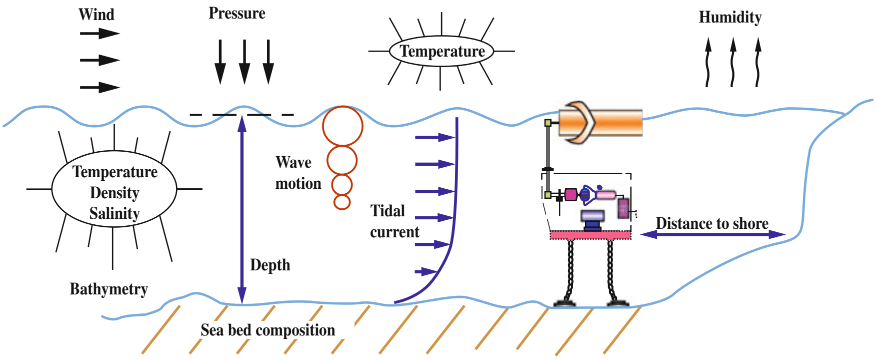

Fig. 1.2 Metocean parameters applicable to marine energy converts, and their primary sub-systems. Adapted from [4]

Most WECs, even the ones with different working principles (see Chap. 2) are very similar from a generic point of view. Most of them consist of the same primary sub-systems, which is due to their common environment and goal (Fig. 1.3).

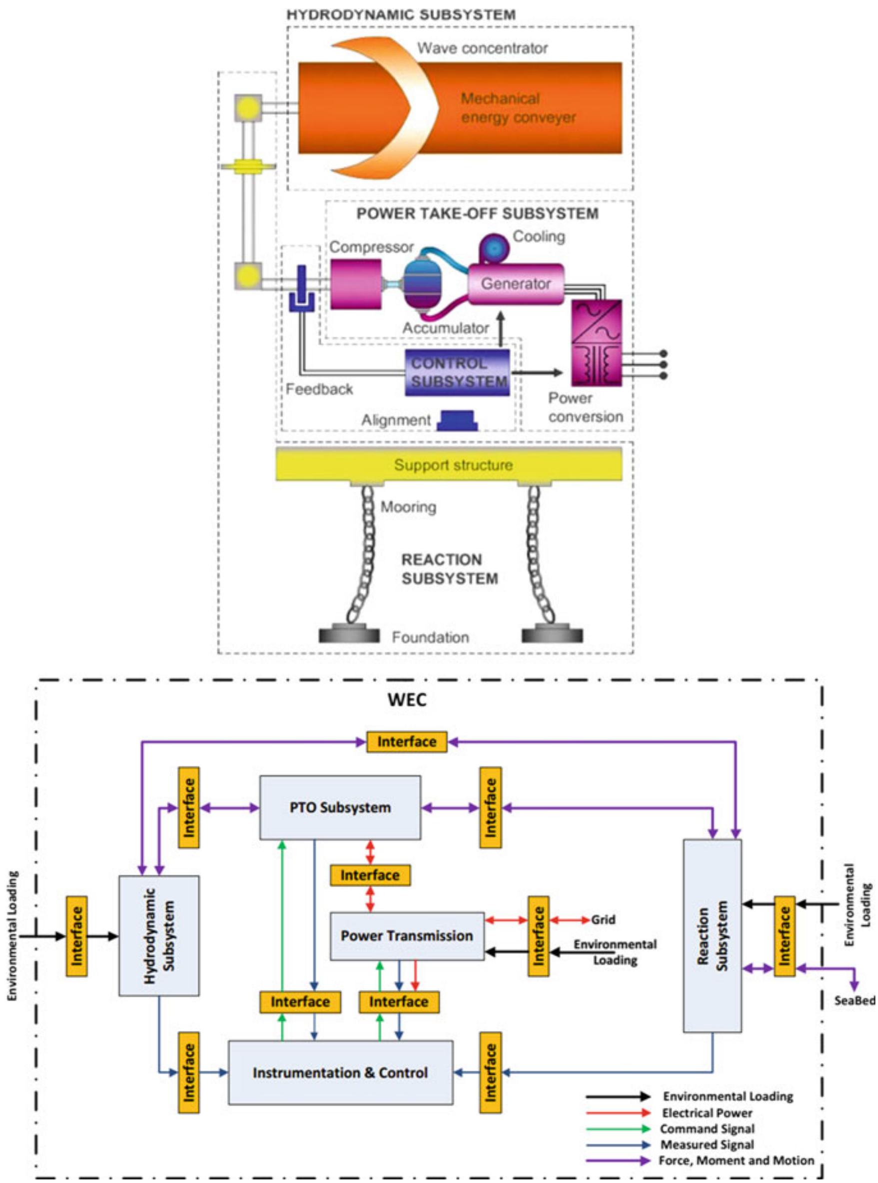

Fig. 1.3 WEC system design breakdown following Equimar (*top*) [5] and DNV (*bottom*) [6]. Courtesy of Equimar and DNV GL

The main sub-systems that are present in (all) WECs have also been introduced widely in literature [4–6] and consist of:

- *The hydrodynamic subsystem* is the primary wave absorption system that exploits the wave power (see Chap. 6). It can be of different types depending on the technology, e.g. oscillating body, oscillating water column and overtopping principle, and it is connected to both the reaction and PTO subsystems against which it will actively transfer forces and motions.
- *The power take-off subsystem* converts the captured wave energy (by the hydrodynamic subsystem) into electricity (see Chap. 8). The PTO systems can be based on different principles, of which some of the most common are hydraulic PTO, direct drive mechanical PTO, linear generators, air turbine and low head water turbine.
- *The reaction subsystem* maintains the WEC into position relative to the seabed (e.g. mooring system) and provides a reaction point for the PTO and/or support for the hydrodynamic subsystem(s) (e.g. fixed reference or support structure) (see Chap. 7).
- *The control (and instrumentation) subsystem* is the intelligent part of the system as it takes care of the control of the WEC and its measurements. It mainly consists of the processors for the automation and electromechanical processes, the sensors and their data acquisition, the communication and data transfer, and the human interface.

These different sub-systems and their interconnections can be presented in different manners, of which two are presented in Fig. 1.3.

1.4 Rules of Thumb for Wave Energy

The following list of "rules of thumb"—covering the essential features, the economics, the design, the PTO systems and the environment of WECS—contains a series of condensed and critical indications which are considered valuable in the assessment of a WEC technology and project. All of them will be addressed in more details in the following chapters.

1.4.1 The Essential Features of a WEC

The following features are the **essential aspects in which a WEC should excel** in order to show long-term economic potential [7]:

- *Survivability*: The WEC requires a reliable mooring system and preferably a passive safety system that can effectively reduce extreme loads. With passive meaning that the safety mechanism can be activated (automatically) without requiring external interaction, such as electricity or other.

- *Reliability and maintainability*: Easy access and inspection of the most essential parts of the WEC. In addition, it would be very beneficial if most (or all) maintenance could be done on the WEC itself at location, without having to bring it back to a harbour.
- *Overall power performance*: The WEC must consist of an efficient wave energy absorbing technology and PTO. It has to produce a sufficiently smooth electrical power and have a high capacity factor. Otherwise, too much energy will be lost over the whole wave-to-wire power conversion chain.
- *Scalability*: At full scale, a WEC needs to be a multi-MW device in order to be economically viable. In order to be able to continue significantly improving its LCoE, it needs to be scalable, meaning that it should be capable of further enlarging its dimensions (like offshore wind turbines do). Many WECs unfortunately reach their optimal dimensions at too low dimensions, making it not possible for them to become multi-MW WECs (>5 MW). This does not include the multiplication of WECs as this will not have a significant influence on the average infrastructural and technology costs and thereby will not significantly improve the LCoE of the WEC or project.
- *Environmental benefit*: WECs are expected to be sustainable energy systems and are thereby expected to have a great environmental benefit and a minimal environmental footprint.

1.4.2 Economic Rules of Thumb

1. For an offshore wind turbine in a 1000 MW farm at 30 m of water depth, an indication of related costs are (more details can be found in Chap. 5 and [8, 9]) as follows:

    - The CapEx per installed MW is approx. 4 million euros.
    - The OpEx/MWh is approximately 30 Euro.
    - The LCoE is approximately 120 Euro/MWh.
    - The general development, infrastructure and commissioning costs, referred to as the base CapEx, of a 3.6 MW offshore wind turbine in a project are in the range of 7.2 million Euros. This includes the development and consent, the installation and commissioning and a part of the balance of plant category, but excludes the tower, the foundations and the technology itself. This cost corresponds to about 45 % of the CapEx [10].
    - The resulting "base" CapEx cost for a 3.6 MW WEC is expected to be slightly less, approx. 6 million Euro, as especially the installation cost should be significantly lower. For smaller WECs, it is expected to be approximately 2 million Euro for a 750 kW WEC.

2. A fast, but reasonably accurate (±50 %), **estimation of the annual energy production** (*AEP*) of a WEC can be obtained by multiplying the mean wave power level (P_{wave}) with the width of the absorber, the overall wave-to-wire efficiency ($\eta_{w2w,}$ which is the weighted average over all the wave conditions), the availability and the yearly production hours:

$$AEP = P_{wave} \times width_{absorber} \times \eta_{w2w} \times availability \times hours_{annual}$$

As an example, for a well-functioning optimized point absorber in a good wave environment, this could give (these indicative values used here are set more in context on other following rules of thumb):

$$AEP = 40\,\mathrm{kW/m} \times 15\,\mathrm{m} \times 20\,\% \times 95\,\% \times 8766 = 999\,\mathrm{MWh/year}$$

This corresponds to an average power production of 114 kW, which gives an installed capacity of 750 kW with a capacity factor of 15 %.
The economic value of this is 150 kEuro/year, assuming a feed-in-tariff of 150 Euro/MWh.
If we assume a WEC that is 10 × larger, we can expect (following the same calculation) that the power production and thereby the revenue will be 10 × larger as well. Furthermore, it can be expected that the capacity factor will be significantly higher, e.g. 30 % or approx. 3.6 MW, as the capacity factor of WECs improves with the amount of wave absorbing bodies that are connected to the same system (see Table 1.3). This is because the different units will significantly smoothen the overall absorbed power as the different absorbers will have a time offset between the moment in which the different absorbers interact with the same wave, and thereby the max-to-mean power ratio is significantly lower of a common PTO system.
3. Combining the base CapEx cost (does not include the technology itself, nor the OpEx) and the revenue from these two different sizes of WEC, **it will take the small WEC about 13 years to repay its base CapEx cost**, while it will only take **about four years for the large WEC**. This indicates clearly that WECs need to be large to be (-come) economically viable, meaning in the multi-MW scale (≥ 1 MW). The assumption that multiple small WECs can be equally as good as one large WEC does not make economic sense as it is too much challenged by the costs of the base CapEx, meaning the project development, infrastructural and commissioning costs.
4. Besides sharing the base costs more efficiently, large WECs have as well multiple other advantages such as:

   - Sharing basic equipment over different wave absorbing bodies, such as mooring systems, weather stations, communication systems, electricity cables and others.
   - Sharing parts of the power take-off (PTO) system, which (usually) results into higher capacity factors and smoother electrical power output.

- The whole system can be commissioned at once, thereby sharing installation and servicing works and equipment, e.g. it only requires one vessel for handling one system.
- Larger structures are more easily accessed as they are more stable, which enables easier inspection of the system and some maintenance could be done on board, without the need of retracting the system to a safe/controlled area.

5. There are various technical assessment ratios for a WEC:

   - The *wave-to-wire efficiency* (η_{w2w}) is the overall efficiency of the system delivering the absorbed energy from the waves to the grid. This value is also based on many underlying specifications, such as the wave conditions, the availability of the system and the maximum power rating, and so needs to be taken very carefully.
   - The *capture width ratio (CWR)* describes the effectiveness of the converter to absorb the energy in the waves. This value is based on many underlying specifications, such as the wave conditions and the size of the wave activated body, and needs thereby to be handled very carefully.
   - The *WEC weight/installed kW* ratio is also often used to indicate how much material is used relative to the power rating of the WEC. This can be a bit misleading as it does not particularly show the type of material (e.g. steel or concrete). It should at least be divided between active structural (load carrying) material and ballast material, as their difference in cost can be as great as a factor 100.
   - The *capacity factor* (also called capacity factor) is the ratio between the average produced power and the installed power on the WEC. It describes the utility rate of the PTO system and is very interesting as it gives an idea of what the WEC delivers (average produced power) and what it costs (driven by installed power). However, this value is also wave condition dependant (location).

   Note that the overall efficiency of a WEC η_{w2w} includes the efficiencies of each power conversion step, between wave and grid, together with the limitations of the system, such as the saturation of the generator. The complete power conversion train is, thereby, composed of at least: hydrodynamic conversion (wave to absorber described by CWR), PTO (absorber to generator), generator and electronics, substation and voltage increase, and grid connection. The availability of the system is not calculated in the overall efficiency as it is dependent on other aspects such as the maintenance possibilities of the system, but is included in the capacity factor.
6. **A very important long-term economic aspect of a WEC is its capability of being scalable in size**, even after it reaches commercial maturity. This can be compared with wind turbines, which keep on being increased in size in order to reduce their LCoE. Different wave-absorbing bodies have different optimal dimensions (see Table 1.2), e.g. the hydrodynamic optimal full-scale diameter of a point absorber will (normally) be between 15–20 m depending on the wave conditions. Large structures with multiple wave absorbing bodies could possibly increase their amount instead of enlarging them.

1.4.3 WEC Design Rules of Thumb

1. The ability for a body to absorb the energy in the waves depends upon its hydrodynamic design (for more details refer to Chap. 6). In general, it can be said that [11]:

> "A good wave absorber must be a good wave-maker."

This means that when a body moves in the water, it will create a wave depending on its shape and motion = radiated wave, e.g. a point absorber will make a circular wave equal in all directions when oscillating vertically. The better that this radiated wave corresponds to the incoming ocean wave, the more efficient this body is in absorbing an incoming ocean wave (Fig. 1.4).

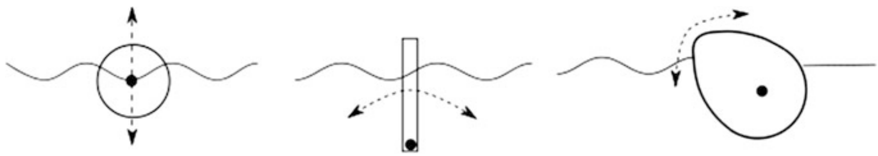

Fig. 1.4 Illustration of the radiated wave by the motion in one direction by three wave-absorbing bodies, from *left to right*: heaving point absorber, pitching flap and pitching Salter's duck

The theoretical limit in wave energy absorption by a body that creates an (anti-) symmetrical radiated wave (e.g. heaving point absorber and pitching flap) is of 50 %. However, for a non-symmetric body (such as a Salter's duck), it may have the ability to absorb almost 100 % incoming wave energy [12].

2. Although there is no clear convergence in technologies yet, there are different main WEC categories. For some of these main categories, **an indicative capture width ratio** on the absorbed power from the waves can be given, based on a collection of published results [13] (Table 1.1).

Table 1.1 Overview of the mean capture width ratio for some of the main WEC types

WEC type	Capture width ratio (%)
Floating overtopping device	17
Oscillating water column	29
Point absorber	16
Pitching flap (bottom fixed)	37

These numbers present a rough indication of the ability of these WEC types to absorb wave energy. This energy still needs to be converted into electricity afterwards. Note that these values need to be taken with care as they can be based on different specifications and assumptions. Some of the most influential parameters are the wave conditions and the relative size (scaling ratio) of the WEC to the waves.

3. **The optimal dimension of the wave absorbing body** and structure of a WEC is usually most strongly linked to the wave period (from all the wave parameters), besides other potentially interfering economic parameters. The peak wave period with the highest annual wave energy contribution (corresponding to the wave energy x probability of occurrence) should be taken into account for this. Table 1.2 gives a rough indication of these dimensions for a full-scale WEC in an average suitable offshore location [13–17].

Table 1.2 Indication of hydrodynamic optimal full-scale dimension of certain WEC technologies for average northern European wave conditions

WEC type	Relevant dimension (m)	
Point absorber	Diameter	12–20
OWC	Length[a]	12–20
OWSC	Thickness[a]	The thicker the better
Floating structures e.g. overtopping WEC	Length	Longer than a wavelength

[a]The width of these wave-activated bodies can be chosen independently, but they still have a strong influence on their hydrodynamic response as it influences the inertia, added mass, drag coefficient and possibly other characteristics of the wave-activated body. However, they tend to be in the range of 12–20 m

These values can indicate the scaling possibilities of a full-scale WEC type and, thereby, indicate the limit in power absorption by a WEC as well.

4. **The power fluctuations of a single WEC** decrease significantly with its amount of wave energy absorbers. The absorbed power from waves fluctuates due to the nature of the waves (time scale of a few seconds), but also due to the fact that waves travel in groups (time scale of a few minutes). These fluctuations are not desirable as they increase the need for oversizing mechanical and electrical equipment and are one of the main barriers to achieve a reliable and cost-efficient technology [18]. Typical max-to-mean ratios in absorbed power are (over 1000 waves period, without physical limitations) [19–22] as follows (Table 1.3).

Table 1.3 Indication of the max-to-mean ratio on the absorbed power by a WEC with different configurations

WEC type	Max-to-mean ratio
Single wave-activated body with one-way PTO	15–30
Single wave activated body with two-way PTO	10–12
OWC with two way PTO	10–15
10 side-by-side located wave-activated bodies (in the wave direction) with two-way PTO	3–7

5. As with wind turbines, several sub-system failures should be expected annually, of which an extensive survey on the **failure rates of several subsystems** of wind turbines is given in (Fig. 1.5). In general, due to serious improvements in the last 5–10 years, although wind turbines endure a high number of malfunctions corresponding they normally only lead to short standstill periods due to the rapid interaction of service teams. They achieve a technical availability of about 98 %, corresponding to a downtime of about 1 week a year [23].
   This should clearly indicate that it is of high importance that all the vital/critical components of WEC should be at least easy to inspect as several malfunctions will occur every year. Even better would be that the components of the WEC are easy to maintain and to interchange, without the necessity of requiring divers or of bringing the WEC back to a protected environment (e.g. harbour). These are both very expensive, require good weather windows, are unpractical and are time-consuming. Fully submerged WECs are, thereby, really difficult to operate as their maintainability is very difficult (remembering that the WEC is located in an area with serious wave conditions).

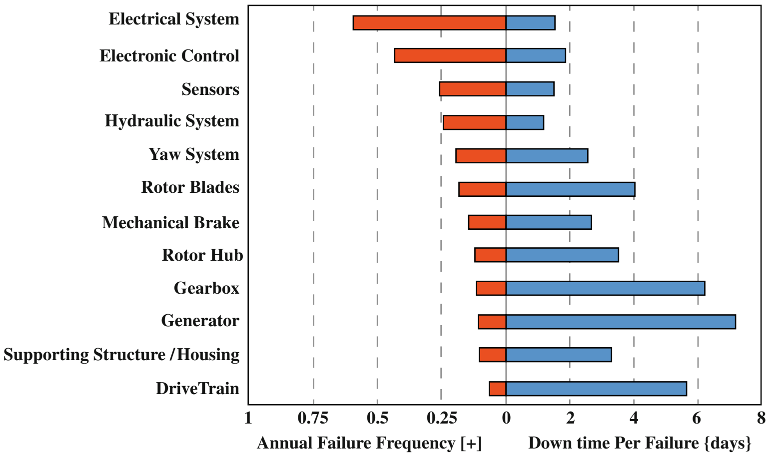

Fig. 1.5 Failure frequency and downtime of components. Adapted from [23]

6. For WEC technologies having a main floating reference structure, it is desirable that the projected length of such a WEC is approximately the same or more than a wavelength for optimal power production. In the opposite case where the wavelength is much longer than the structure, the structure will start moving with the wave.
7. **Mooring of floating structures** can be problematic and is in general expensive. Some basic rules of thumb are as follows:

   - Although WECs are typically more efficient in steep waves, they result in larger surge offsets, relative to their rest position.

- Surge motions of a moored floating structure are especially large under the event of breaking waves, which also result in significantly higher wave loads on the structure.
- The durability of the mooring system is even further challenged under short-term repetitive wave events such as wave groups (which is very common).

A golden rule is to moor a floating WEC outside of the area where wave breaking occurs due to water depth interferences.

8. **Exceptionally high (peak) loads occur with sudden stops of bodies in motion**. This can occur within the structure or sub-systems, e.g. due to physical end-stops in the PTO system (e.g. in linear generators or hydraulic pistons) or snap shocks when stretching out mooring lines.

1.4.4 Power Take-Off Rules of Thumb

1. The **PTO of a wave-activated body is the most efficient when its motion is restricted to only one degree of freedom**. Otherwise, the wave-activated body will always chose to move in the direction of the least resistance and thereby avoid PTO interaction. Furthermore, limiting its motions to one degree of freedom;

   - Reduces the complexity of the PTO system and the possible amount of load cases.
   - Optimises its efficiency and facilitates its control as the exact motion of the wave activated body is known.

2. PTO systems for WECs are normally required to convert a slow oscillating movement combined with high forces (induced by the nature of the waves) to a fast rotation in one direction (required by an electrical motor). Thereby, there is a wide range of different types of PTO systems, which all present advantages and inconveniences in term of efficiency, control, complexity and cost (see Chap. 8). **Indicative values of efficiencies for these different types of PTOs** (from absorbed wave energy to generator) are [24] (Table 1.4).
   Note that other aspects of the PTO system can be as well of high importance, such as the ability to;

Table 1.4 Overview of the indicative efficiency for different PTO systems (see more on Chap. 8)

PTO system	Efficiency (%)
Hydraulic	65
Water	85
Air	55
Mechanical	90
Direct drive	95

- Temporarily store/smooth energy.
- Handle short-term power overload.
- Handle sudden system faults and possible control losses.

3. Advanced control strategies of the wave absorbing body through the PTO system can typically greatly enhance the overall power production. However, this will also entail significantly higher loads and wear on the structure and components of the system.
4. The **PTO is also much more efficient working against a fixed reference**. This fixed reference can be the seabed or a large structure that does not move under the wave absorbing action of the system. Otherwise, a lot of energy will potentially be transferred into motions of other linked bodies.

1.4.5 Environmental Rules of Thumb

1. **The power performance of a WEC is much better in steep waves** as these results in more frequent and/or larger motions of the wave energy absorber. In long (swell) waves, the motions of the water surface are less frequent and slower, which lead to slower and smaller motions of the wave-activated body.
2. **Important aspects of a good location for WECs**:

   - Good average wave energy content, e.g. >15 kW/m, as this is the source of energy.
   - Good average wave steepness, e.g. >1.5 %, as the performance of WECs is significantly higher in steep waves.
   - Low max-to-mean ratio in terms of significant wave heights, as you build (≈pay for) the WEC design to endure a 100-year wave while it produces energy (≈earnings) relative to the average wave condition.
   - Low monthly wave energy content variation, as it facilitates stable power production and improves the capacity factor when the wave climate is consistent over the whole year. However, this makes installation and maintenance more difficult as weather windows are less frequent and shorter.
   - Proximity to the coast, infrastructure and end-user as it significantly reduces CapEx and OpEx costs related to the project.
   - Reasonable water depth (e.g. 30–60 m), which can seriously affect the mooring and cabling cost.

It can hardly be expected to find a place where all of these criteria are met perfectly. However, it is the best balance in between them, resulting in the best overall LCoE, which should dictate the value of a project at a certain location. Some of the better locations are the following:

- South and West coasts below the tropic of Capricorn (e.g. Australia, New Zealand, South Africa and Chile): high average wave power and low seasonal variability and low 100-year wave to mean wave ratio.
- East coasts below the tropic of Capricorn (e.g. Australia, New Zealand, South Africa, Argentina, Uruguay and South Brazil): medium average wave power, with low seasonal variability and low 100-year wave to mean wave ratio.
- West coast of United States: medium average wave power, with low seasonal variability and low 100-year wave to mean wave ratio.
- North Atlantic (Europe and East coast US): high average wave power and steep waves, but high seasonal variability and high 100-year wave to mean wave ratio.

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